

CDS

TECHNICAL MEMORANDUM NO. CIT-CDS 95-020
July, 1995

“LMI approach to mixed performance objective controllers: application to Robust H_2 Synthesis”

Raffaello D’Andrea

Control and Dynamical Systems
California Institute of Technology
Pasadena, CA 91125

Report Documentation Page			Form Approved OMB No. 0704-0188		
<p>Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p>					
1. REPORT DATE JUL 1995	2. REPORT TYPE	3. DATES COVERED 00-00-1995 to 00-00-1995			
4. TITLE AND SUBTITLE LMI approach to mixed performance objective controllers: application to Robust H2 Synthesis			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) California Institute of Technology, Control and Dynamical Systems, Pasadena, CA, 91125			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 19	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

LMI approach to mixed performance objective controllers: application to Robust \mathcal{H}_2 Synthesis

Raffaello D'Andrea
Electrical Engineering, M/S 116-81
California Institute of Technology
Pasadena, CA 91125
EMAIL: raff@hot.caltech.edu
PHONE: 818-395-8419

Keywords: Convex Synthesis, Robust \mathcal{H}_2

Abstract

The problem of synthesizing a controller for plants subject to arbitrary, finite energy disturbances and white noise disturbances via Linear Matrix Inequalities (LMIs) is presented. This is achieved by considering white noise disturbances as belonging to a constrained set in l_2 . In the case of where only white noise disturbances are present, the procedure reduces to standard \mathcal{H}_2 synthesis. When arbitrary, finite energy disturbances are also present, the procedure may be used to synthesize general mixed performance objective controllers, and for certain cases, Robust \mathcal{H}_2 controllers.

1 Introduction

In the standard robust control paradigm, the signal space which characterizes performance is equivalent to that which captures a system's uncertainty. For example, \mathcal{H}_∞ tools are used when dealing with bounded energy (or power) gain uncertainty (see [12], [10], [18]), while when working with l_∞ disturbances, the uncertainty is assumed to be of finite amplitude gain (see [9]). While it is often the case that the particular characterization of the uncertainty is not critical to the design process, the signal space used to characterize the performance often is. In particular, one of the common complaints among control design engineers which use \mathcal{H}_∞ methods is that the resulting designs tend to be sluggish and overly conservative. As an alternative, \mathcal{H}_2 designs are often employed, but they lack the robustness properties of \mathcal{H}_∞ designs (see [5]) which can readily be extended to encompass a system's uncertainty. The attractive feature of \mathcal{H}_2 designs is their gain interpretation; they minimize the power output when the disturbances are assumed to be white noise or impulses. This is in contrast to \mathcal{H}_∞ designs, which minimize the energy to energy (or power to power) gain; in many applications, modeling the

disturbances as arbitrary signals is a poor modeling choice, and thus \mathcal{H}_∞ designs lead to low performance controllers.

A desirable control design strategy would be one which has the input-output gain interpretation of the \mathcal{H}_2 norm, but can readily accommodate \mathcal{H}_∞ bounds on the uncertainty.

In [15], a framework is developed whereby white noise signals are captured in a deterministic setting. The main motivation behind this approach was the reconciling of the worst case setting, natural when considering robustness issues, with the stochastic setting. This framework proved very natural when addressing the so-called *Robust \mathcal{H}_2 Analysis* problem, which was solved in [13] and [14].

This approach will be used in this paper to tackle the problem of *Robust \mathcal{H}_2 Synthesis* for a restricted class of problems; in particular, rank one synthesis problems with time varying uncertainty. This will be achieved by solving an auxiliary problem, that of synthesizing a controller for plants subject to arbitrary, finite energy disturbances and white noise disturbances.

Other work in this area includes [2], [6], [19] and [17]. Also worth noting is research on the so called *mixed $\mathcal{H}_2 / \mathcal{H}_\infty$* problem, where only nominal stability and nominal \mathcal{H}_2 performance are considered (see [1], [8]).

The paper is organized as follows: we begin with some mathematical preliminaries, followed by a review of the notions introduced in [15] with regards to capturing noise signals as elements of a set. The problem is then posed and solved, followed by a discussion on computational issues. The problem of robust disturbance rejection is then addressed, and it is shown how these types of problems can be re-formulated in the general problem setup previously solved. We conclude with an example which illustrates the tools developed and their numerical properties.

2 Preliminaries

Most of the notation in this paper is standard. We restrict ourselves to discrete time systems. The space of square summable sequences is denoted l_2 ; when the spatial structure is relevant, it is referred to as l_2^p . The 2-norm of a signal d in l_2 is denoted $\|d\|$. The unit ball of l_2 signals is denoted \mathbf{Bl}_2 , and consists of all l_2 signals whose norm is less than or equal to one. The discrete time, unit delay operator is denoted λ . The truncation operator P_T is defined as

$$(P_T x)(t) := \begin{cases} x(t) & \text{for } t \leq T \\ 0 & \text{for } t > T \end{cases} \quad (1)$$

Causal, finite dimensional, linear time invariant systems will be denoted FDLTI. A causal linear map G over l_2 is bounded if the restriction of G to l_2 is a bounded operator, with induced l_2 norm denoted $\|G\|$. The transfer function representation of FDLTI system G

is denoted $\hat{G}(\lambda)$. The linear fractional transformation (LFT) between two systems G and K is denoted $G \star K$, and is defined as:

$$G \star K := G_{11} + G_{12}K(I - G_{22}K)^{-1}G_{21} \quad (2)$$

where

$$G = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}$$

when the inverse of $(I - G_{22}K)$ is well defined. $\mathbf{B}\Delta$ is the set of linear, but otherwise arbitrary, operators whose induced 2-norm is less than or equal to 1. For two subsets of l_2 , S_1 and S_2 , the *approximation error* of S_1 with S_2 is defined as

$$D(S_1, S_2) := \sup_{s_1 \in S_1} \inf_{s_2 \in S_2} \|s_1 - s_2\| \quad (3)$$

$D(S_1, S_2)$ is a measure of how well S_2 captures the elements of S_1 . For a constant matrix A , its maximal element is denoted

$$\|A\|_{\mathbf{M}} := \max_{i,j} |A_{i,j}| \quad (4)$$

3 Deterministic Noise Sets

We begin by reviewing the notions introduced in [15] to capture white noise in sets. Given a signal $n \in l_2^m$, its *autocorrelation function* is defined as

$$R_n(\tau) := \sum_{t=-\infty}^{\infty} n(t)n^T(t + \tau) \quad (5)$$

Note that there is no time averaging in the definition above, as would be used for power signals, since we are dealing with finite energy signals. Given positive integer N and positive number γ , we define the following set of autocorrelation functions:

$$\mathcal{R}_{N,\gamma}^m := \left\{ R(\tau) : \mathbb{Z} \rightarrow \mathbb{R}^{m \times m} \middle| \begin{array}{l} R(-\tau) = R^T(\tau) \\ \|R(0) - I\|_{\mathbf{M}} \leq \gamma \\ \|R(\tau)\|_{\mathbf{M}} \leq \gamma, \quad 1 \leq \tau \leq N \end{array} \right\} \quad (6)$$

and corresponding signal set

$$\mathcal{W}_{N,\gamma}^m := \left\{ n \in l_2^m \mid R_n(\tau) \in \mathcal{R}_{N,\gamma}^m \right\} \quad (7)$$

In particular, when $\gamma = 0$, we have

$$\mathcal{W}_N^m := \mathcal{W}_{N,0}^m \quad (8)$$

It is shown in [15] how the worst case gain from \mathcal{W}_N^m to l_2 approaches the \mathcal{H}_2 norm in the limit as N goes to infinity, the rate of convergence being exponential.

4 Problem Formulation

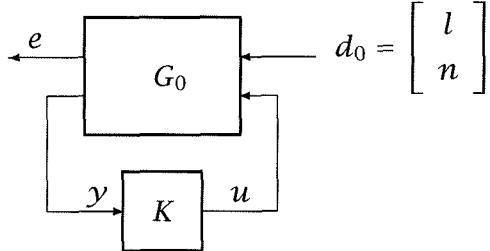


Figure 1: Problem Formulation

The problem formulation is as follows; given positive integer N and FDLTI system G_0

$$G_0 = \begin{bmatrix} G_{11}^l & G_{11}^n & G_{12} \\ G_{21}^l & G_{21}^n & G_{22} \end{bmatrix} \quad (9)$$

find internally stabilizing (see [21]) FDLTI system K such that

$$\sup_{l \in \mathbf{Bl}_2, n \in \mathcal{W}_N^m} \|(G_0 \star K)d_0\|^2 < 1 \quad (10)$$

The performance objective is absorbed into plant G_0 ; in general, the performance objective will be decreased until a controller no longer exists which satisfies (10). We will later show how the solution to the above problem may be used to solve a variety of robustness problems. The above problem formulation is interesting in its own right, however; it may be the case that some of the disturbance signals may be arbitrary, in this case l , while the others are white noise, such as n . For example, this may be the case when tracking a reference signal l (which may be weighted to restrict tracking over a certain frequency range), in the presence of sensor noise or other random disturbance n .

5 Solution

We will provide a solution to the above problem in a series of steps. The first consists of recalling the solution of controller synthesis when the disturbances are subject to implicit constraints, presented in [3]. The next step consists of parametrizing sets \mathcal{W}_N^m in image form. The final step is to combine these image representations with the solution provided in the first step to solve (10).

5.1 Synthesis with implicit constraints

The following is a review of the main results in [3]. Consider the following subset of l_2 ,

$$\mathcal{H} = \left\{ d \in l_2 \mid \begin{array}{ll} \|H_i d\|^2 \leq 1 & 1 \leq i \leq c \\ \|L_j d\|^2 = \|J_j d\|^2 & 1 \leq j \leq \bar{c} \end{array} \right\} \quad (11)$$

where the H_i , L_j and J_j are constant matrices. Consider the following constrained feasibility problem: let system G and set \mathcal{H} be given. Find a stabilizing controller K such that

$$\sup_{d \in \mathcal{H}} \|(G \star K)d\|^2 < 1 \quad (12)$$

It is shown in [3] that such a controller K exists if and only if there exist symmetric matrices S, T, W, Z (of a given spatial structure) such that

$$V \left(R^T \begin{bmatrix} S & 0 \\ 0 & I \end{bmatrix} R - \begin{bmatrix} S & 0 \\ 0 & Z \end{bmatrix} \right) V^T < 0 \quad (13)$$

$$U^T \left(R \begin{bmatrix} T & 0 \\ 0 & W \end{bmatrix} R^T - \begin{bmatrix} T & 0 \\ 0 & I \end{bmatrix} \right) U < 0$$

$$\begin{bmatrix} T & I \\ I & S \end{bmatrix} > 0$$

$$\begin{bmatrix} Z & I \\ I & W \end{bmatrix} > 0$$

$$C^T Z C < 1$$

where U , V , R and C are constant matrices which depend on the state space representation for G and the constraint set \mathcal{H} . A state space representation for K may then be constructed from R , S and T (the details may be found in [3] and [11]). The above is a convex feasibility problem, and may be solved using numerical packages such as *LMI Lab* [7].

5.2 Image Representation for \mathcal{W}_N^m

The solution provided in the previous section cannot be utilized to directly solve (10); in order to directly specify \mathcal{W}_N^m , H_i , L_j and J_j need to be systems, not constant matrices (see [2]). What we would like to do is construct an alternate representation for \mathcal{W}_N^m which is consistent with the solution provided in the previous section.

Let N and m be given. Define

$$\begin{aligned}\hat{U}_k(\lambda) &:= \frac{1 + \lambda^k}{\sqrt{8N}} \\ \hat{U}_k(\lambda) &:= \frac{1 - \lambda^k}{\sqrt{8N}} & 1 \leq k \leq N \\ U &:= [U_1 \ \bar{U}_1 \dots U_N \ \bar{U}_N] \\ V &:= \text{diag } [U, U, \dots, U]\end{aligned}\tag{14}$$

where $V \in \mathcal{RH}_{\infty}^{m \times (2mN)}$, ie., V consists of m copies of U along the “diagonal”. Then it may be verified that

$$\hat{V}\hat{V}^* = \frac{1}{2N}I_m\tag{15}$$

ie., \hat{V} and \hat{U} are co-inner, and $\|\hat{V}\|_{\infty} = \|\hat{U}\|_{\infty} = \frac{1}{\sqrt{2N}}$.

Define $\tilde{n} \in l_2^{2mN}$ as follows:

$$\begin{aligned}\tilde{n} &:= (\tilde{n}_1, \dots, \tilde{n}_m) \\ \tilde{n}_i &:= (n_{i,1}, \bar{n}_{i,1}, \dots, n_{i,N}, \bar{n}_{i,N})\end{aligned}\tag{16}$$

and the following set of constraints:

$$\begin{array}{lll}\mathbf{C}_1: & \langle n_{i,k}, n_{i,k} \rangle \leq 1, \langle \bar{n}_{i,k}, \bar{n}_{i,k} \rangle \leq 1 & 1 \leq i \leq m, \quad 1 \leq k \leq N \\ \mathbf{C}_2: & \langle n_{i,k}, n_{j,k} \rangle - \langle \bar{n}_{i,k}, \bar{n}_{j,k} \rangle = 0 & 1 \leq i < j \leq m, \quad 1 \leq k \leq N \\ \mathbf{C}_3: & \langle n_{i,k}, \bar{n}_{j,k} \rangle - \langle \bar{n}_{i,k}, n_{j,k} \rangle = 0 & 1 \leq i < j \leq m, \quad 1 \leq k \leq N \\ \mathbf{C}_4: & \langle n_{i,k}, n_{j,k} \rangle + \langle \bar{n}_{i,k}, \bar{n}_{j,k} \rangle = 0 & 1 \leq i < j \leq m, \quad k = 1\end{array}$$

The constraint set \mathcal{N} is then defined as:

$$\mathcal{N} := \{\tilde{n} \in l_2^{2mN} | \mathbf{C}_1, \mathbf{C}_2, \mathbf{C}_3, \mathbf{C}_4 \text{ are satisfied}\}\tag{17}$$

The image set $\widetilde{\mathcal{W}}_{N,\gamma}^m$ may now be defined:

$$\widetilde{\mathcal{W}}_{N,\gamma}^m := \{n \in l_2^m | n = V\tilde{n}, \tilde{n} \in \mathcal{N}, \|n_i\| \geq 1 - \gamma \text{ for } 1 \leq i \leq m\}\tag{18}$$

For $\gamma = 1$, we define

$$\widetilde{\mathcal{W}}_N^m := \widetilde{\mathcal{W}}_{N,1}^m\tag{19}$$

which corresponds to no explicit norm constraint on n_i . The following theorem outlines how \mathcal{W}_N^m and $\widetilde{\mathcal{W}}_{N,\gamma}^m$ are related, and is crucial to the synthesis results which follow:

Theorem 1

1. $\widetilde{\mathcal{W}}_{N,0}^m = \mathcal{W}_N^m$.
2. $\mathcal{W}_N^m \subset \widetilde{\mathcal{W}}_{N,\gamma}^m$ for $\gamma \geq 0$.
3. $D(\widetilde{\mathcal{W}}_{N,\gamma}^m, \mathcal{W}_N^m)$ is upper semi-continuous as a function of γ at $\gamma = 0$.

Before proving Theorem 1, we will need the following two Lemmas:

Lemma 1

$$S := \{n \in l_2^m \mid 2NV^*n \in \mathcal{N}, \|n_i\|^2 = 1 \text{ for } 1 \leq i \leq m\} = \widetilde{\mathcal{W}}_{N,0}^m \quad (20)$$

Proof of Lemma 1:

It is clear by setting $\tilde{n} = 2NV^*n$ that $S \subset \widetilde{\mathcal{W}}_{N,0}^m$; we will thus show that $\widetilde{\mathcal{W}}_{N,0}^m \subset S$. Let $n \in \widetilde{\mathcal{W}}_{N,0}^m$, with corresponding \tilde{n} . For each component, by constraints **C₁**, $\|\tilde{n}_i\|^2 \leq 2N$, which implies $\|n_i\|^2 \leq 1$. Thus $\|n_i\|^2 = 1$, $\|\tilde{n}_i\|^2 = 2N$.

Since \hat{U} is co-inner, $\exists \hat{U}_\perp \in \mathcal{RH}_\infty^{(2N-1) \times 2N}$ such that $\sqrt{2N} \begin{bmatrix} \hat{U} \\ \hat{U}_\perp \end{bmatrix}$ is unitary. Thus for each i , \tilde{n}_i can be uniquely decomposed as

$$\tilde{n}_i = U^*v_i + U_\perp^*w_i \quad (21)$$

where $v_i \in l_2$, $w_i \in l_2^{2N-1}$. Furthermore, $\|\tilde{n}_i\|^2 = \|U^*v_i\|^2 + \|U_\perp^*w_i\|^2$. From this we may conclude that $v_i = 2Nn_i$, and that $\|v_i\| = \|U^*v_i\|^2 = \|\tilde{n}_i\|^2 = 2N$; thus $w_i = 0$, and $\tilde{n}_i = 2NU^*n_i$. This gives $\tilde{n} = 2NV^*n$, as required. \square

Lemma 2 Given $R \in \mathcal{R}_{N,\gamma}^m$, where $\gamma < \frac{1}{m(N+1)^2}$, there exists a signal $x \in l_2^+$ such that $R_x(\tau) = R(\tau)$ for $\tau \in [-N, N]$.

The proof of Lemma 2 may be found in the Appendix. We are now in a position to prove Theorem 1:

Proof of Theorem 1:

We begin by showing how n is constrained when $2NV^*n \in \mathcal{N}$. Let $\tilde{n} = 2NV^*n$. Thus

$$\begin{aligned} n_{i,k} &= 2NU_k^*n_i && (22) \\ \bar{n}_{i,k} &= 2N\bar{U}_k^*n_i & \text{for } 1 \leq i \leq m, 1 \leq k \leq N \end{aligned}$$

For the above, it can be verified that constraints **C₁** to **C₄** are equivalent to :

$$\begin{aligned} \mathbf{C}_1 : \quad &\|n_i\|^2 + \langle n_i, \lambda^k n_i \rangle \leq 1 & 1 \leq i \leq m, & 1 \leq k \leq N \\ &\|n_i\|^2 - \langle n_i, \lambda^k n_i \rangle \leq 1 & 1 \leq i \leq m, & 1 \leq k \leq N \\ \mathbf{C}_2 : \quad &\langle n_i, \lambda^k n_j \rangle + \langle n_i, \lambda^{-k} n_j \rangle = 0 & 1 \leq i < j \leq m, & 1 \leq k \leq N \\ \mathbf{C}_3 : \quad &\langle n_i, \lambda^k n_j \rangle - \langle n_i, \lambda^{-k} n_j \rangle = 0 & 1 \leq i < j \leq m, & 1 \leq k \leq N \\ \mathbf{C}_4 : \quad &\langle n_i, n_j \rangle = 0 & 1 \leq i < j \leq m \end{aligned}$$

Proof of 1: Let $n \in \mathcal{W}_N^m$. The above constraints are then trivially satisfied, proving $n \in S$; thus by Lemma 1, $n \in \widetilde{\mathcal{W}}_{N,0}^m$. Now let $n \in \widetilde{\mathcal{W}}_{N,0}^m$, or equivalently, $n \in S$. It is then straightforward to show that the above constraints imply that $n \in \mathcal{W}_N^m$, as required.

Proof of 2: This follows from 1. and $\widetilde{\mathcal{W}}_{N,\gamma}^m \subset \widetilde{\mathcal{W}}_{N,\gamma_0}^m$ for $0 \leq \gamma \leq \gamma_0$.

Proof of 3: Let $\epsilon > 0$ be given. It will be shown that there exists a $\gamma_0 > 0$ such that for all $0 \leq \gamma \leq \gamma_0$, $D(\widetilde{\mathcal{W}}_{N,\gamma}^m, \mathcal{W}_N^m) < \epsilon$. Let $\gamma_0 > 0$ be fixed. For any $0 \leq \gamma \leq \gamma_0$, $n \in \widetilde{\mathcal{W}}_{N,\gamma}^m$ and corresponding \tilde{n} , we may decompose \tilde{n} as in equation (21) yielding:

$$\tilde{n}_i = 2NU^*n_i + U_\perp^*w_i, \quad 1 \leq i \leq m \quad (23)$$

Since $\|\tilde{n}_i\| \leq \sqrt{2N}$ and $\|n_i\| \geq 1 - \gamma_0$, it follows that $\|w_i\| \leq 2N\sqrt{2\gamma_0}$. Applying constraints **C₁** through **C₄** to (23) results in

$$\begin{aligned} \mathbf{C}_1 : \quad & \|n_i\|^2 + \langle n_i, \lambda^k n_i \rangle \leq 1 + O(\|w_i\|); & 1 \leq i \leq m, & 1 \leq k \leq N \\ & \|n_i\|^2 - \langle n_i, \lambda^k n_i \rangle \leq 1 + O(\|w_i\|) & 1 \leq i \leq m, & 1 \leq k \leq N \\ \mathbf{C}_2 : \quad & |\langle n_i, \lambda^k n_j \rangle + \langle n_i, \lambda^{-k} n_j \rangle| \leq O(\|w_i\|) & 1 \leq i < j \leq m, & 1 \leq k \leq N \\ \mathbf{C}_3 : \quad & |\langle n_i, \lambda^k n_j \rangle - \langle n_i, \lambda^{-k} n_j \rangle| \leq O(\|w_i\|) & 1 \leq i < j \leq m, & 1 \leq k \leq N \\ \mathbf{C}_4 : \quad & |\langle n_i, n_j \rangle| \leq O(\|w_i\|) & 1 \leq i < j \leq m \end{aligned}$$

We may thus conclude that there exists a constant C , independent of γ_0 , such that $n \in \mathcal{W}_{N,C\sqrt{\gamma_0}}$. Since $n \in l_2$, there exists a $T \in \mathbb{Z}^+$ such that $\|n_i - \frac{P_T n_i}{\|P_T n_i\|}\| \leq 2\gamma_0$. Define

$$\begin{aligned} \hat{n} &:= (\hat{n}_1, \dots, \hat{n}_m) \\ \hat{n}_i &:= (1 - \frac{\epsilon}{6\sqrt{m}}) \frac{P_T n_i}{\|P_T n_i\|} \end{aligned} \quad (24)$$

It can be shown that for $\gamma_0 \leq \frac{1}{2C}$, $\hat{n} \in \mathcal{W}_{N,2C\sqrt{\gamma_0}}$. Furthermore, $\|n - \hat{n}\| \leq \frac{\epsilon}{6} + 2\sqrt{m}\gamma_0$. Let

$$\begin{aligned} C_1 &= 1 - \left(1 - \frac{\epsilon}{6\sqrt{m}}\right)^2 \\ R(\tau) &= -C_1^{-1}R_{\hat{n}}(\tau), \quad 1 \leq |\tau| \leq N \\ R(0) &= C_1^{-1}(I - R_{\hat{n}}(0)) \end{aligned} \quad (25)$$

Then it can be verified that $R \in \mathcal{R}_{N,2C\sqrt{\gamma_0}C_1^{-1}}^m$. By Lemma 2, for $\gamma_0 \leq \frac{C_1^2}{8C^2m^2(N+1)^4}$, there exists signal $x \in l_2^+$ such that $R_x(\tau) = R(\tau)$ for $\tau \in [-N, N]$.

Define

$$d = \hat{n} + C_1 \lambda^{N+T+1} x \quad (26)$$

Then

$$\begin{aligned} R_d(\tau) &= R_{\hat{n}}(\tau) + C_1 R_x(\tau) \\ &= 0 \quad \tau \neq 0 \\ &= I \quad \tau = 0 \end{aligned} \quad (27)$$

Thus $d \in \mathcal{W}_N^m$. Furthermore,

$$\begin{aligned}\|n - d\| &\leq \|n - \hat{n}\| + \|\hat{n} - d\| \\ &\leq \frac{\epsilon}{6} + 2\sqrt{m}\gamma_0 + \frac{\epsilon}{3}\end{aligned}\tag{28}$$

Choosing

$$\gamma_0 = \min \left\{ \frac{1}{2C}, \frac{C_1^2}{8C^2m^2(N+1)^4}, \frac{\epsilon}{6\sqrt{m}} \right\} \tag{29}$$

gives the required results. \square

5.3 Image Representations and Implicit Constraints

We are now in a position to provide a solution to (10) by combining the results of Sections 5.1 and 5.2. The following theorem outlines how we may replace set \mathcal{W}_N^m with $\widetilde{\mathcal{W}}_N^m$. The idea is to penalize disturbance $n \in \widetilde{\mathcal{W}}_N^m$ in such a way that the worst case error will occur when n is as large as possible; this in effect will force n to be in \mathcal{W}_N^m :

Theorem 2 *Given M_l and $M_n \in \mathcal{RH}_\infty$, then*

$$\sup_{l \in \mathbf{Bl}_2, n \in \mathcal{W}_N^m} \|M_l l + M_n n\|^2 < 1 \tag{30}$$

if and only if there exists k_0 such that $\forall k \geq k_0$,

$$\sup_{l \in \mathbf{Bl}_2, n \in \widetilde{\mathcal{W}}_N^m} \left\| \frac{kn}{M_l l + M_n n} \right\|^2 < mk^2 + 1 \tag{31}$$

Proof:

(31) \Rightarrow (30): Since $\mathcal{W}_N^m \subset \widetilde{\mathcal{W}}_N^m$, it is clear that

$$\sup_{l \in \mathbf{Bl}_2} \sup_{n \in \mathcal{W}_N^m} \left\| \frac{k_0 n}{M_l l + M_n n} \right\|^2 < mk_0^2 + 1$$

Furthermore, $\forall n \in \mathcal{W}_N^m$, $\|k_0 n\|^2 = mk_0^2$. Thus (30) is implied, as required.

(30) \Rightarrow (31): Assume (30) is satisfied. Then, by continuity of $D(\widetilde{\mathcal{W}}_{N,\gamma}^m, \mathcal{W}_N^m)$ at $\gamma = 0$, $\exists \gamma_0 > 0$ such that

$$\sup_{l \in \mathbf{Bl}_2} \sup_{n \in \widetilde{\mathcal{W}}_{N,\gamma_0}^m} \|M_l l + M_n n\|^2 \leq C_0 < 1$$

for some constant C_0 . Furthermore,

$$\sup_{l \in \mathbf{Bl}_2} \sup_{n \in \widetilde{\mathcal{W}}_N^m} \|M_l l + M_n n\|^2 \leq (\|M_l\|_\infty + \sqrt{m}\|M_n\|_\infty)^2 := C_1$$

Suppose (31) is not satisfied. Then, $\forall k, \exists n \in \widetilde{\mathcal{W}}_N^m$ and $l \in \mathbf{Bl}_2$ such that

$$\|n\|^2 \geq m + \frac{\frac{1+C_0}{2} - \|M_l l + M_n n\|^2}{k^2}$$

In particular, let $k = \sqrt{\frac{C_1}{\gamma_0}}$. Then it follows that $n \in \widetilde{\mathcal{W}}_{N,\gamma_0}^m$. Furthermore, since $\|n\|^2 \leq m$,

$$\|M_l l + M_n n\|^2 \geq \frac{1+C_0}{2} > C_0$$

which contradicts our assumption, as required. \square

The following corollary may be applied to controller synthesis:

Corollary 1 *Let G_0 be given. For any controller K , let*

$$M(K) = \begin{bmatrix} M_l(K) & M_n(K) \end{bmatrix} := G_0 \star K \quad (32)$$

Then there exists a K such that

$$\sup_{l \in \mathbf{Bl}_2, n \in \mathcal{W}_N^m} \|M_l(K)l + M_n(K)n\|^2 < 1 \quad (33)$$

if and only if there exist K and k_0 such that $\forall k \geq k_0$,

$$\sup_{l \in \mathbf{Bl}_2, \tilde{n} \in \mathcal{N}} \frac{1}{1+mk^2} \left\| \begin{bmatrix} kV\tilde{n} \\ M_l(K)l + M_n(K)V\tilde{n} \end{bmatrix} \right\|^2 < 1 \quad (34)$$

The proof of the above follows from Theorem 2 and $\widetilde{\mathcal{W}}_N^m = \{n | n = V\tilde{n}, \tilde{n} \in \mathcal{N}\}$. Next, note that constraints **C₁** to **C₄**, which characterize \mathcal{N} , are equivalent to the following constraints:

C₁ :	$\ n_{i,k}\ ^2 \leq 1, \ \bar{n}_{i,k}\ ^2 \leq 1$	$1 \leq i \leq m,$	$1 \leq k \leq N$
C₂ :	$\ n_{i,k} + n_{j,k}\ ^2 + \ \bar{n}_{i,k}\ ^2 + \ \bar{n}_{j,k}\ ^2 = \ \bar{n}_{i,k} + \bar{n}_{j,k}\ ^2 + \ n_{i,k}\ ^2 + \ n_{j,k}\ ^2$	$1 \leq i < j \leq m,$	$1 \leq k \leq N$
C₃ :	$\ n_{i,k} + \bar{n}_{j,k}\ ^2 + \ \bar{n}_{i,k}\ ^2 + \ n_{j,k}\ ^2 = \ \bar{n}_{i,k} + n_{j,k}\ ^2 + \ n_{i,k}\ ^2 + \ \bar{n}_{j,k}\ ^2$	$1 \leq i < j \leq m,$	$1 \leq k \leq N$
C₄ :	$\ n_{i,k} + n_{j,k}\ ^2 + \ \bar{n}_{i,k} + \bar{n}_{j,k}\ ^2 = \ n_{i,k}\ ^2 + \ n_{j,k}\ ^2 + \ \bar{n}_{i,k}\ ^2 + \ \bar{n}_{j,k}\ ^2$	$1 \leq i < j \leq m,$	$k = 1$

Furthermore, $l \in \mathbf{Bl}_2$ is equivalent to $\|l\|^2 \leq 1$. Thus $\tilde{n} \in \mathcal{N}$ and $l \in \mathbf{Bl}_2$ can be captured in a form consistent with \mathcal{H} in (11). Finally, let $\alpha = \frac{1}{\sqrt{1+mk^2}}$. Then by setting

$$G = \begin{bmatrix} 0 & k\alpha V & 0 \\ \alpha G_{11}^l & \alpha G_{11}^n V & \alpha G_{12} \\ G_{21}^l & G_{21}^n V & G_{22} \end{bmatrix} \quad (35)$$

(34) may be solved by the method presented in Section 5.1.

6 Computation

A controller K may be found which verifies (34) using the methods of Section 5.1 for a given k ; thus one would choose k , and synthesize a controller. In order to solve the original problem of (33) and (10), however, we need to ensure that $k > k_0$. It is possible to find a lower bound for k_0 given the open loop system G , N , and how closely we want to approximate the optimal solution. This bound, however, will more likely than not be too conservative to be of any use. In practice, k should be chosen as large as the numerical algorithm allows. This is a topic for future research.

For a given N and m , it is also worth noting how much constraints C_1 through C_4 cost, in terms of the number of constraints (which is linearly related to the number of decision variables required):

	COST
C_1	$2mN$
C_2	$\frac{1}{2}m(m - 1)N$
C_3	$\frac{1}{2}m(m - 1)N$
C_4	$\frac{1}{2}m(m - 1)$
TOTAL	$m \left(2N + (m - 1)(N + \frac{1}{2}) \right)$

Table 1: Cost of Constraints

Thus the growth is linear in N and quadratic in m . In order to keep the computational complexity down, constraints C_2 through C_4 may be omitted, with the result being that each component of n will tend to be a white noise signal, but may be correlated to other components. The particular nature of the problem will dictate how conservative this omission will be.

In addition, G consists of an augmented version of G_0 . In particular, V results in an extra mN number of states. Since the number of decision variables grows as the *square* of the number of states of the plant, quadratic growth is unavoidable, both in N and in m .

7 Application to Robust \mathcal{H}_2 Synthesis: Robust Disturbance Rejection

We will show the types of robustness problems that may be solved using the machinery developed in this paper. Consider the setup of Figure 2. Given P , it is required to design K such that disturbances n_d , along with measurement errors n_e , have a small effect on plant output e . The plant is subject to multiplicative, unstructured uncertainty Δ , with associated weight W_t . Since n_d and n_e are disturbances, one may know more about

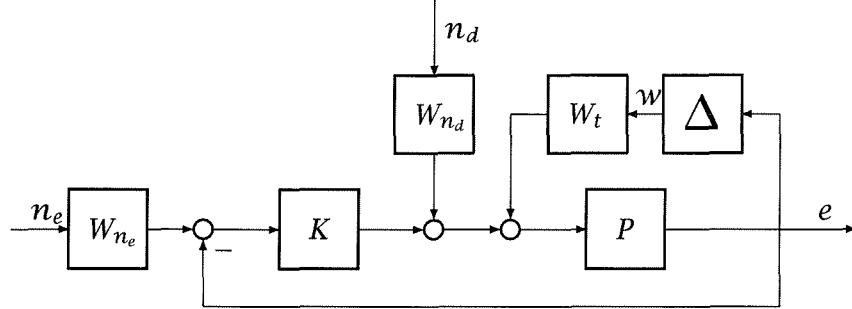


Figure 2: Robust Disturbance Rejection

their spectral content than that they are filtered, but otherwise arbitrary, l_2 signals. In many cases, a good model for disturbances is *colored white noise*, or filtered white noise. One may therefore want to model n_d and n_e as white noise signals, filtered by W_{n_d} and W_{n_e} , respectively. An example where this may arise is n_e being sensor noise and n_d an impulsive (or known) disturbance (it is also straightforward to consider the case where n_d is an arbitrary disturbance in Bl_2 , etc.).

The relevant equation describing the system is

$$\begin{aligned} e &= SPW_t \Delta e + SPW_{n_d} n_d + TW_{n_e} n_e \\ &= (I - SPW_t \Delta)^{-1} (SPW_{n_d} n_d + TW_{n_e} n_e) \\ &:= M_1 n_d + M_2 n_e \end{aligned} \tag{36}$$

where

$$\begin{aligned} S &:= (I + PK)^{-1} \\ T &:= PK(I + PK)^{-1} \end{aligned} \tag{37}$$

The Robust Disturbance Rejection problem is as follows:

Robust Disturbance Rejection

For a given N , find an internally stabilizing K such that

$$\sup_{\Delta \in \mathbb{B}\Delta} \sup_{(n_d, n_e) \in \mathcal{W}_N^m} \|M_1 n_d + M_2 n_e\| < 1 \tag{38}$$

The above may be converted to a condition which does not involve Δ :

Theorem 3 K solves the Robust Disturbance Rejection problem iff K is an internally stabilizing controller and

$$\sup_{l \in \text{Bl}_2} \sup_{(n_d, n_e) \in \mathcal{W}_N^m} \|SPW_t l + SPW_{n_d} n_d + TW_{n_e} n_e\| < 1 \tag{39}$$

The proof of the above is equivalent to the one in [3], where n_d and n_e are assumed to be arbitrary l_2 disturbances (the idea is that since Δ is an arbitrary contractive map, Δe may be replaced by l). The above can now be cast into the framework of Section 4. In general, many robust synthesis problems may be solved using this technique (see [3]); the only restriction is that the uncertainty (possibly more than one block) have e as their input.

8 Example

We present a simple example for which the solution is known. In particular, we will use the machinery developed thus far to synthesize an optimal \mathcal{H}_2 controller for a given plant. We are not proposing this method for synthesizing optimal \mathcal{H}_2 controllers, since exact solutions exist, but rather wish to explore the properties of our algorithm on a simple example.

Consider the following unstable, non-minimum phase, SISO plant:

$$\hat{P} = \frac{-\lambda + \frac{1}{2}}{\lambda + \frac{2}{3}} \quad (40)$$

The goal is to minimize the \mathcal{H}_2 norm of the sensitivity function, $S = (1 + PK)^{-1}$. The generalized plant G_0 for this problem is

$$G_0 = \begin{bmatrix} 1 & -P \\ 1 & -P \end{bmatrix} \quad (41)$$

The following table summarizes the results obtained using standard synthesis methods (see [4]):

	\mathcal{H}_∞ Analysis	\mathcal{H}_2 Analysis	Optimal Controller
\mathcal{H}_∞ Synthesis	1.1429	1.1429	$\hat{K} = \frac{5}{12}$
\mathcal{H}_2 Synthesis	1.7143	0.9897	$\hat{K} = 1 + 0.3889\lambda$

Table 2: Exact synthesis results

We then repeated the synthesis for $k = 0, 1, 3, 10, 100$ with N fixed at 4, and for $N = 0, 1, 2, 3, 4$ with k fixed at 100. The resulting closed loop responses are depicted in Figure 3, along with the optimal \mathcal{H}_2 and \mathcal{H}_∞ results for comparison purposes.

For the first plot, the flat response is that of the optimal \mathcal{H}_∞ closed loop, while the response with the highest peak is that of the optimal \mathcal{H}_2 closed loop. The five values in between correspond to different values of k , ascending values of k corresponding to ascending values of the \mathcal{H}_∞ norm.

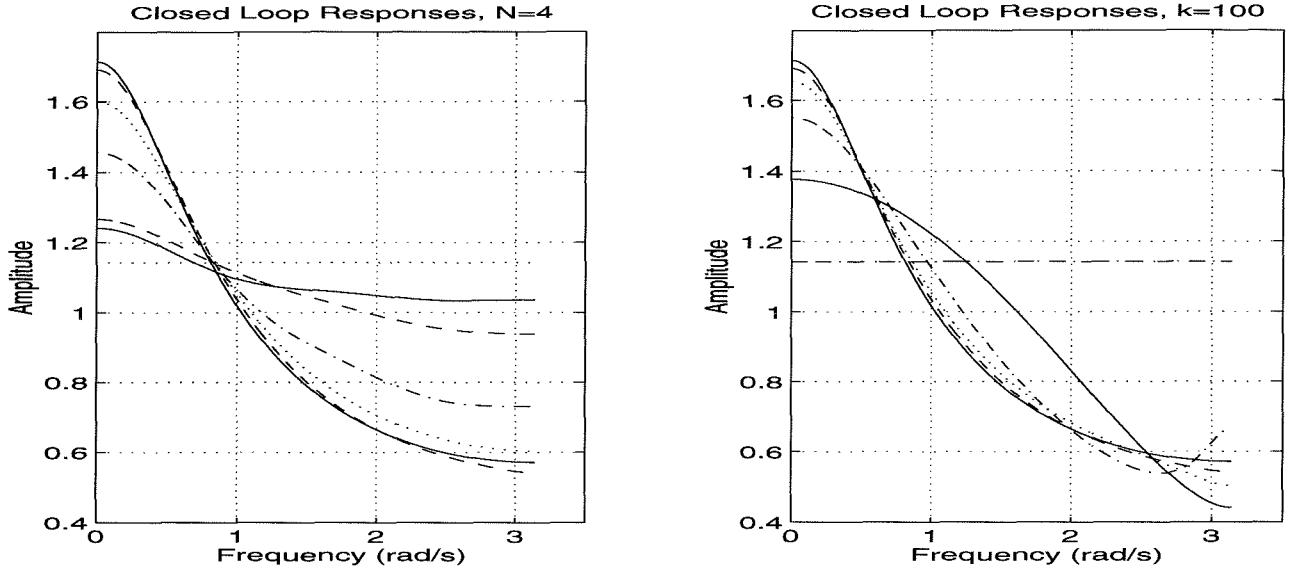


Figure 3: Synthesis with constraints

In the second plot, the \mathcal{H}_∞ and \mathcal{H}_2 designs are also included for comparison purposes. Ascending values of N correspond to ascending values of the \mathcal{H}_∞ norm. Note that only six curves seem to be present in the second plot, since the $N = 0, k = 100$ design is virtually identical to the \mathcal{H}_∞ design, as expected.

The $N = 4, k = 100$ controller was

$$\hat{K} = \frac{1.0079 + 0.3953\lambda}{1 + 0.0306\lambda} \quad (42)$$

which is very close to the optimal \mathcal{H}_2 controller. Furthermore, the closed loop \mathcal{H}_2 norm for this design was 0.9899, and the \mathcal{H}_∞ norm was 1.690, again extremely close to the optimal \mathcal{H}_2 design. Note, however, that the $N = 4$ design isn't necessarily the best one. For example, the $N = 1$ design has a closed loop \mathcal{H}_2 norm of 1.021 and \mathcal{H}_∞ norm of 1.377; As a percentage, the $N = 1$ design has \mathcal{H}_2 norm which is approximately 3% larger than the $N = 4$ design, but \mathcal{H}_∞ norm which is 23% smaller. The point is that most of the reduction in the \mathcal{H}_2 norm occurred with only one constraint; pushing harder to reduce the \mathcal{H}_2 norm only serves to increase the \mathcal{H}_∞ norm.

There is an interesting connection between the tools developed in this paper when applied to standard \mathcal{H}_2 optimization and known results on \mathcal{H}_2 synthesis. In particular, it is known that synthesizing the optimal \mathcal{H}_2 controller for a given system is equivalent to synthesizing the optimal \mathcal{H}_∞ controller for the same system multiplied by an appropriate weight. Thus our method can be thought of as searching for a feasible controller *and* the correct weighting function simultaneously. This interpretation is also valid for the general case, ie., when there is also a signal l .

9 Conclusions

The tools presented in this paper allow for controller synthesis when the disturbances are a combination of arbitrary, norm bounded l_2 signals, and signals in set \mathcal{W}_N^m . For a fixed N , the solution takes the form of an LMI, for which good numerical packages exist. To solve the problem where noise signal n is perfectly white (ie., satisfies an arbitrarily large number of correlation constraints), N will have to be arbitrarily large; this seems to be unavoidable, however, since the optimal controller will probably be infinite dimensional. The strength of this approach, however, is that designing for a fixed N gives us both sufficient *and necessary* conditions for the existence of a controller. By inspecting the nature of \mathcal{W}_N^m and the resulting closed loop system, the design engineer may then decide whether the solution is acceptable, or a larger value of N is required; this is the case in the example presented, where it isn't clear whether the $N = 4$ design is better than the $N = 1$ design.

This relates to the view that optimization techniques should only be used as design tools, and should be flexible enough to allow the design engineer to customize the results to the particular problem at hand; for real problems, the objective is almost never to minimize the closed loop \mathcal{H}_∞ or \mathcal{H}_2 norms (or anything in between, for that matter). The best one can do is to provide flexible enough tools to automate some of the design process, and let the engineer do the rest. This is the case with standard \mathcal{H}_∞ theory, where the problem of optimal control design is reduced to that of finding appropriate weights; the design becomes iterative, where weight selection is determined by the previous closed loop system. The tools provided in this paper can thus be thought of as a method to automate some of the weight selection process, and as a result, allow for more complex designs to be performed.

Acknowledgements

The author would like to thank Fernando Paganini, Geir Dullerud, and John Doyle for the helpful discussions. This work was funded by NSERC and AFOSR.

Appendix

Proof of Lemma 2 (see [16]): Let

$$Q = \begin{bmatrix} \frac{1}{N+1}R(0) & \frac{1}{N}R(1) & \cdots & R(N) \\ \frac{1}{N}R(-1) & \frac{1}{N+1}R(0) & \cdots & \frac{1}{2}R(N-1) \\ \vdots & \ddots & & \vdots \\ R(-N) & \frac{1}{2}R(-N+1) & \cdots & \frac{1}{N+1}R(0) \end{bmatrix} \in \mathbb{R}^{m(N+1) \times m(N+1)} \quad (43)$$

By Gergorshin's Circle Theorem (see [20]), we may bound each eigenvalue of Q from below by

$$\frac{1 - m\gamma}{N + 1} - \sum_{k=1}^N m\gamma > \frac{1 - \gamma m(N + 1)^2}{N + 1} \quad (44)$$

Since $\gamma < \frac{1}{m(N+1)^2}$, $Q > 0$. Thus there exists $P > 0$ such that $P^2 = Q$. Let

$$\bar{P} := \begin{bmatrix} P \\ 0 \end{bmatrix} \in \mathbb{R}^{2m(N+1) \times m(N+1)} \quad (45)$$

i.e., we have added $m(N + 1)$ rows of zeros to P . Now define $x(t)$ as follows

$$\begin{bmatrix} x(0) \\ \vdots \\ x(2m(N + 1)^2) \end{bmatrix} := \text{vec}(\bar{P}) \quad (46)$$

i.e., formed by stacking the columns of \bar{P} into one long vector. We claim that $R_x(\tau) = R(\tau)$ for $|\tau| \leq N$. Partition P as

$$P = \begin{bmatrix} P_{00} & \cdots & P_{0N} \\ \vdots & \ddots & \vdots \\ P_{N0} & \cdots & P_{NN} \end{bmatrix} \quad (47)$$

which implies

$$R(\tau) = (N + 1 - |\tau|) \sum_{k=0}^N P_{ik} P_{kj}, \quad j = i + \tau \quad (48)$$

Further partitioning each P_{ik} as

$$P_{ik} = \begin{bmatrix} (P_{ik})_1 & \cdots & (P_{ik})_m \end{bmatrix} \quad (49)$$

and using the fact that $P_{kj} = P_{jk}^\top$, we have

$$R(\tau) = (N + 1 - |\tau|) \sum_{k=0}^N \sum_{l=1}^m (P_{ik})_l (P_{jk})_l^\top, \quad j = i + \tau \quad (50)$$

It thus follows from the definition of $x(t)$ in (46), for $0 \leq \tau \leq N$,

$$\begin{aligned}
R_x(\tau) &= \sum_{j=0}^N \sum_{l=1}^m \sum_{i=0}^{N-\tau} (P_{ij})_l (P_{i+\tau,j})_l^T \\
&= \sum_{i=0}^{N-\tau} \sum_{j=0}^N \sum_{l=1}^m (P_{ij})_l (P_{i+\tau,j})_l^T \\
&= \sum_{i=0}^{N-\tau} \frac{1}{N+1-\tau} R(\tau) \\
&= R(\tau)
\end{aligned} \tag{51}$$

A similar argument holds for negative τ . □

References

- [1] Bernstein D.S., Haddad W.H., "LQG Control with an \mathcal{H}_∞ Performance Bound: A Riccati Equation Approach", IEEE Trans. A.C., Vol 34, 3, pp. 293-305, 1989.
- [2] D'Andrea R., Paganini F., "Controller Synthesis for Implicitly Defined Uncertain Systems", Proceedings 1994 CDC, Orlando, FL, pp 3679-3684.
- [3] D'Andrea R., "Convex Conditions for Controller Synthesis via Implicit Constraints", Submitted 1995 CDC, New Orleans.
- [4] Dahleh, M.A., Diaz-Bobillo I.J., *Control of Uncertain Systems*, Prentice Hall, 1995.
- [5] Doyle J.C., "Guaranteed margins for LQG regulators", IEEE Trans. A.C., vol 23(4), pp. 756-757, 1978.
- [6] Doyle J.C. et. al., *Mixed \mathcal{H}_2 and \mathcal{H}_∞ Performance Objectives II: Optimal Control* IEEE Trans. A.C., Vol 39, 8, pp. 1575-1587.
- [7] Gahinet P. et. al., *The LMI Control Toolbox*, Beta-Release, Nov. 1994, The MathWorks Inc.
- [8] Khargonekar P., Rotea M., "Mixed $\mathcal{H}_2 / \mathcal{H}_\infty$ Control: A Convex Optimization Approach", IEEE Trans. C.C., Vol 36, 7, pp. 824-837, 1991.
- [9] Khammass M., Pearson J.B., "Performance Robustness of Discrete-Time Systems with Structured Uncertainty", IEEE Trans. A.C., vol AC-36, 4, pp 398-412, 1991.
- [10] Megretski A., Treil S., "Power Distribution Inequalities in Optimization and Robustness of Uncertain Systems", Journal of Mathematical Systems, Estimation and Control, Vol 3, No.3, pp 301-319, 1993.
- [11] Packard A., "Gain Scheduling via Linear Fractional Transformations", System and Control Letters, Vol:22 (2), 1994, pp. 79-92.
- [12] Packard A., Doyle J.C., "The Complex Structured Singular Value", Automatica, Vol. 29, No. 1, pp. 71-109
- [13] Paganini F., D'Andrea R., and Doyle J.C., "Behavioral Approach to Robustness Analysis", Proceedings 1994 ACC, Baltimore, MD., pp. 2782-2786.

- [14] Paganini F., “*Necessary and Sufficient Conditions for Robust \mathcal{H}_2 Performance*”, Submitted 1995 CDC, New Orleans.
- [15] Paganini F., *Set “Descriptions of White Noise and Worst Case Induced Norms”*, Proceedings 1993 CDC, San Antonio, Texas, pp. 3658-3663.
- [16] Paganini F., personal communication.
- [17] Petersen I., McFarlane D., Rotea M., “*Optimal guaranteed cost control of discrete-time uncertain linear systems*” 12th IFAC World Congress, Sydney, Australia, pp. 407-410.
- [18] Shamma J., “*Robust Stability with Time Varying Structured Uncertainty*”, IEEE Trans. A.C., Vol 39, 4,pp 714-724, 1994.
- [19] Stoerovogel A.A., “*The Robust \mathcal{H}_2 Control Problem: A Worst-Case Design*”, IEEE Trans. A.C.,Vol 38,9, pp. 1358-1370, 1993.
- [20] Strang G., *Linear Algebra and its Applications* Harcourt Brace Jovanovich, Publishers, 1988.
- [21] Zhou K., Doyle J.C., Glover K., *Optimal and Robust Control*, to appear 1995.